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Article

Enabling the Use of Earth Observation Data for Integrated Water Resource Management in Africa with the Water Observation and Information System

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Abstract: The Water Observation and Information System (WOIS) is an open source software tool for monitoring, assessing and inventorying water resources in a cost-effective manner using Earth Observation (EO) data. The WOIS has been developed by, among others, the authors of this paper under the TIGER-NET project, which is a major component of the TIGER initiative of the European Space Agency (ESA) and whose main goal is to support the African Earth Observation Capacity for Water Resource Monitoring. TIGER-NET aims to support the satellite-based assessment and monitoring of water resources from watershed to cross-border basin levels through the provision of a free and powerful software package, with associated capacity building, to African authorities. More than 28 EO data processing solutions for water resource management tasks have been developed, in correspondence with the requirements of the participating key African water authorities, and demonstrated with dedicated case studies utilizing the software in operational scenarios. They cover a wide range of themes and information products, including basin-wide characterization of land and water resources, lake water quality monitoring, hydrological modeling and flood forecasting and mapping. For each monitoring task, step-by-step workflows were developed, which can either be adjusted by the user or largely automatized to feed into existing data streams and reporting schemes. The WOIS enables African water authorities to fully exploit the increasing EO capacity offered by current and upcoming generations of satellites, including the Sentinel missions.

Keywords: water resource management; information systems; Earth observation; Africa

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1. Introduction

Despite having experienced more than 10 years of continuous economic growth, Africa today faces great water resource management challenges. With 10% of the world's renewable water resources, more than 60 trans-boundary basins, a low level of water development and utilization and increasing population, Africa's future economic growth will continue to be constrained by the development of its water resources. Today, in many African countries, water policies and management decisions are based on sparse and unreliable information. In this challenging context, water information systems are fundamental for improving water governance and implementing integrated water resource management (IWRM) successfully. This water information gap is a major limitation for putting in practice IWRM plans to face the current and coming challenges of the African water sector. Recognizing the utility of satellite data for IWRM, the European Space Agency (ESA), through its participation in the Committee on Earth Observation Satellites (CEOS), launched the TIGER initiative in 2002 [1]. The TIGER initiative supports water authorities, technical centers and other stakeholders in the African water sector to enhance their capacity to collect and use water-relevant geo-information to better monitor, assess and inventorize their water resources by exploiting Earth Observation (EO) products and services [2]. Currently, the TIGER initiative consists mainly of the TIGER Capacity Building Facility (including support for selected research projects) and the TIGER-NET project.

The aim of TIGER-NET is to build a pre-operational capacity for water resources monitoring based on EO technologies at mandated African water authorities. The initial key host institutions already actively involved in TIGER-NET encompass major river basin authorities (Nile Basin Initiative, Lake Chad Basin Commission, Zambezi Watercourse Commission and Volta Basin Authority), national ministries and agencies (Department of Water Affairs South Africa; the Hydrologic Division of the Namibian Ministry of Agriculture, Water and Forestry; the Department of Water Affairs of the Zambian Ministry of Mines, Energy and Water Development; DR Congo National Agency of Meteorology and Teledetection by Satellite; Instituto Nacional de Meteorologia of Mozambique), as well as international research and humanitarian organizations (International Water Management Institute, United Nations World Food program and Action Against Hunger).

The TIGER-NET project builds on the 10 years of experience gained within TIGER demonstration and capacity building activities in order to develop practices and tools required for an eventual transfer of EO information into the day-to-day work of water authorities. A steering committee consisting of experts from the African Water Facility, African Ministers' Council on Water-Technical Advisory Committee (AMCOW-TAC), the Water Research Commission of South Africa, United Nations' Economic Commission for Africa (UN-ECA) and United Nations Educational, Scientific and Cultural Organization's International Hydrological Programme (UNESCO IHP), provides guidance with regard to the African water sector priorities. The major focus of the project is on developing, demonstrating and training a user-driven, open-source Water Observation and Information System (WOIS), which enables the production and application of a range of satellite EO-based information products needed for IWRM in Africa. Importantly, one of the aims is to develop the necessary local capacity for accessing and exploiting historic satellite data, as well as future Sentinel observations [3]. Free data access, free licensing and the ability to integrate with existing systems are key advantages of the WOIS, which should enable its extension to other countries and regions in Africa and beyond, as well as encourage user-driven sustainability in terms of funding and operation.

Against this background, this paper outlines the development framework of the WOIS software to illustrate current features of the system and to review selected application cases demonstrating the real impact of the system on enhancing water management and integrated water resource management plans in Africa.

2. Technical Development and WOIS Design

2.1. User Driven Design and Development

The WOIS has been designed in direct response to user requirements, *i.e.*, based on extensive consultation, review and analysis of the user needs in terms of their current technological and personnel capacity, application-specific monitoring demands, as well as geo-information and system needs. In general, the common requirement was for an easy-to-operate, open-source end-to-end system enabling a full capacity to establish water-related information for monitoring, analysis and reporting (maps, tables and graphs) per sub-watershed for IWRM. While the system requirements were found to be very common among the host institutions, the specific application requirements and information demands varied according to the variety of IWRM challenges faced in the different river basins of Africa. Those applications included mapping and monitoring of lake water quality, flood monitoring, land degradation and land cover characterization, water bodies and wetlands mapping, hydrological modeling, hydrological characterization (soil moisture, precipitation and evapotranspiration), soil erosion potential indicators, as well as urban water supply and sanitation planning support.

The users have also been part of the actual WOIS development, which has followed the agile principles for software development in which the developers stay flexible and responsive to the latest issues reported by the users [4]. The work has progressed via feedback loops where the developers have tackled any outstanding issues, prioritized based on their importance to the users, before testing the solutions and integrating them into the software system. At the end of each loop, a working product was delivered to the users, who would then provide more feedback to the developers. In the case of WOIS software, the initial users were the EO specialists involved in the system design and application creation, and later, during the system installation and demonstration, the development was driven directly by feedback from the African water management authorities.

2.2. System Architecture and Functionality

As no single software package could provide all of the requested functionality, the underlying design principle was to develop a system that uses dedicated software for specific tasks and where the various software components are integrated into a single graphical user interface (GUI). All of the WOIS software components (Figure 1) are based on proven and stable open-source (free) software and include:

- QGIS 2.2 [5]: extensive and user friendly GIS (software website: qgis.org (accessed on 9 March 2014));
- GRASS GIS 6.4.3 [6]: modular GIS consisting of raster and vector analysis algorithms (software website: grass.osgeo.org (accessed on 9 March 2014));
- BEAM 5.0 [7]: processing of optical and thermal ESA data products (software website: brockmann-consult.de/cms/web/beam (accessed on 9 March 2014));
- NEST 5.1 [8]: processing of radar ESA data products (software website: earth.esa.int/web/nest/home (accessed on 9 March 2014));
- Orfeo Toolbox 4.0.0 [9]: high resolution image processing (software website: orfeo-toolbox.org (accessed on 9 March 2014));
- Soil Water Assessment Tool (SWAT) 2.9 [10]: hydrological modeling (software website: swat.tamu.edu (accessed on 9 March 2014));
- R 3.1.0 language scripts [11]: statistical and graphical tools (software website: www.r-project.org (accessed on 9 March 2014));
- PostGIS 2.1.3 [12]: geospatial database (software website: postgis.net (accessed on 9 March 2014)).

In addition, Python scripts [13] were used for automating certain tasks and integrating the different software. WOIS combines full versions of the component software into a multipurpose system consisting of a storage container for the geodata, extraction and processing of the EO data through customized processing facilities and integrative tools and models aimed at decision support, e.g., hydrological modeling and GIS-embedded visualization and analysis tools.

Selected examples of generic WOIS capabilities are georeferencing, reprojection and radiometric calibration of optical and SAR data obtained by (among others) MERIS and ASAR sensors onboard the Envisat satellite and the SAR sensor onboard the RADARSAT-2 satellite, terrain analysis, image classification and change detection, time-series analysis, interactive data exploration and export (tables and graphs), map composing and 3D visualization. WOIS also provides a hydrological modeling framework for scenario-based model development and operational simulation and forecasting. Furthermore, a PostGIS database enables centralized or distributed storage of vector data, while a library of import/export functions ensures the ability to integrate and/or connect to external IT infrastructures and databases.

There are no minimum system requirements for using WOIS, and the system performance depends on the size of the raster and vector data sets that are to be analyzed and the computational complexity of the analysis tasks to be performed. Therefore, for optimal performance it is recommended for the host computer to have at least an Intel Core i5-3570 processor, 8 GB of RAM, 1 TB of hard disk space and to be running Windows 7 (64 bit) or higher. However, WOIS has been successfully installed and operated on 32- and 64-bit computers falling far below the above specifications, with Windows versions ranging from XP to 8.

Figure 1. Open-source software packages integrated as part of the Water Observation and Information System (WOIS).

2.3. Component Integration

QGIS was chosen as the central integrating platform, due to its clear and accessible GUI, strong development community, ease of implementing additional functionalities through Python plugins and its high level of interoperability with major GIS data formats through the use of the Geospatial Data Abstraction Library (GDAL/OGR) library [14]. Moreover, the integrated Processing toolbox, formerly known as SEXTANTE [15], brings the ability to easily incorporate geoprocessing algorithms from various applications into QGIS. It acts as a joint repository for a wide range of algorithms, some native to QGIS and others imported from external applications, such as GRASS or the Orfeo Toolbox. It also allows for easy incorporation of R and Python scripts. The algorithms included in the Processing toolbox integrate seamlessly with the QGIS capabilities of data I/O, rendering or map creation.

The Processing toolbox is based on modular architecture with limited core functionality and the ability to easily add geoalgorithms from different applications through provider modules. The core functionality is responsible for, for example, data passing to and from QGIS or automatic GUI creation for each algorithm. The provider modules take care of exposing the algorithms to the toolbox, communicating with the external applications and setting up the correct environment for algorithm execution. The external communication is mostly performed through command line-based instructions, although it is also possible to engage the external applications through their Python bindings.

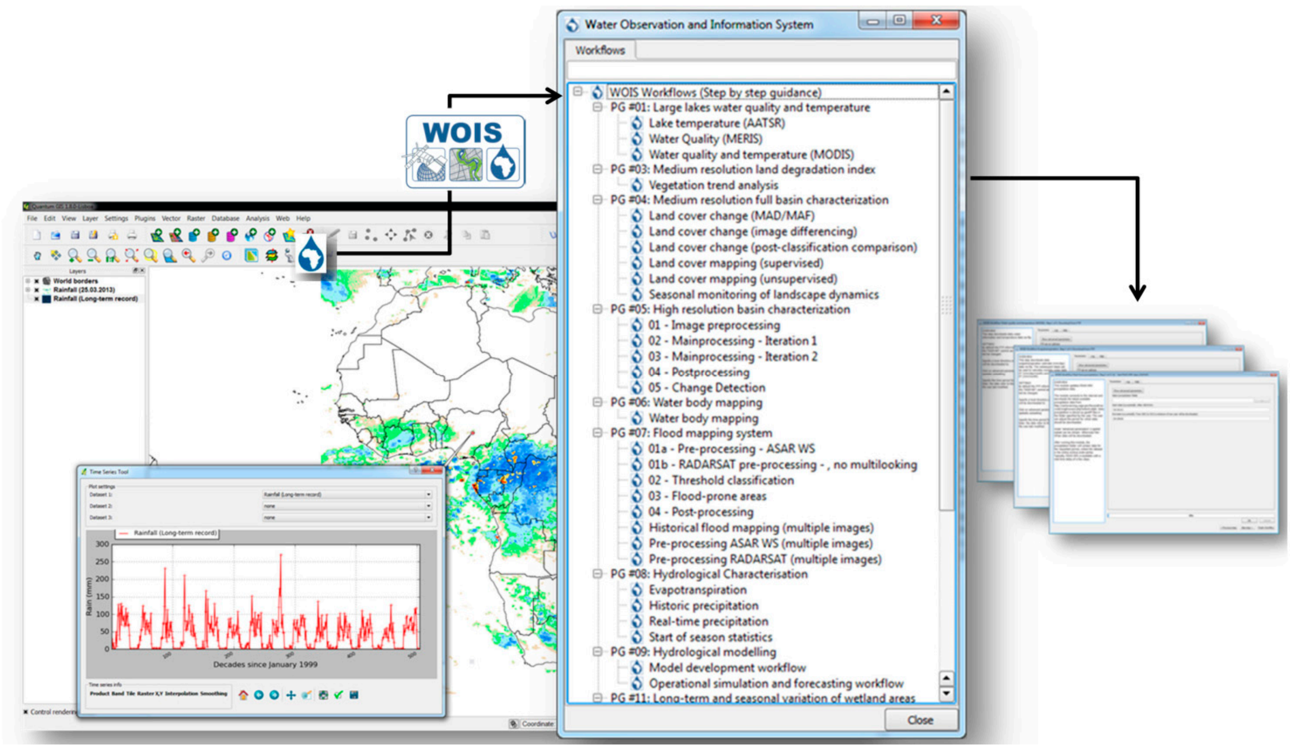
The Processing toolbox already included modules linking with many of the WOIS software components. However, an algorithm provider for BEAM and the Next ESA SAR Toolbox (NEST) had to be developed as an additional QGIS plugin. Since NEST is built on top of BEAM's core libraries, it was possible to create a common provider for the two applications. The communication with BEAM and NEST is performed through the Graph Processing Framework (GPF), which takes care of low level issues, such as efficient data input and output or multi-threading. The GPF can be called on a command line, and through passing of an XML file a chosen operator can be executed with the given settings. Since the toolboxes for the upcoming Sentinel missions will be based on BEAM and NEST [16,17], the use of GPF ensures an easy implementation path for Sentinel algorithms into WOIS.

Similarly, a QGIS plugin was developed for incorporating SWAT modeling inside QGIS processing. The plugin has functionality for setting up and calibrating SWAT models, acquiring climate data from outside sources, running the models, assimilating observations and plotting the results.

2.4. Processing Workflows

One of the features of the QGIS Processing toolbox is the modeler functionality, which enables the creation of models combining any of the algorithms present in the toolbox. The modeler comes with an easy to use drag and drop GUI, making it possible to quickly create advanced processing models. A similar functionality was developed as part of WOIS inside a new QGIS plugin, to enable the creation of processing workflows through an easy to use GUI.

Figure 2. The WOIS graphical user interface, including the embedded workflow library (**center**) and wizard-based processing workflow (**right**).



The workflows transparently combine algorithms from the different providers and guide the users with wizard-like, step-by-step instructions through the available processing chains. They are intended for novice and intermediate users, as an introduction to the theory and practice of using EO data for various tasks related to their field of interest. Therefore, they were designed to be used with minimal technical skills, although in some cases, expert local knowledge or GIS/modelling experience is still required. The workflows are accessible from the WOIS toolbox, which is available through the QGIS GUI (Figure 2) and functions as a workflow library. More advanced users may choose to explore the full suite of algorithms and tools available from the Processing toolbox in order to create their own workflows or models.

3. Water Resource Applications

The operational and practical use of the WOIS to support IWRM in Africa has been demonstrated via a series of user-specific demonstration cases, some of which are described in this section and summarized in Table 1 [18–20]. They show the depth and versatility of WOIS for performing numerous tasks related to water resource management and the advantages of combining the capabilities of the different WOIS component software.

Table 1. Summary of the WOIS demonstration cases described in this paper.

Name	Key Output Variables	Region of Application	Accuracy/Performance	Limitations	Required User Skills
Large lakes water quality and temperature monitoring	Water surface temperature, chlorophyll concentration, suspended sediments concentration.	Lake Victoria, Lake Chad	Spatiotemporal variation in accordance with expected patterns. MODIS-derived water quality is of lesser accuracy.	Works on medium to coarse resolution data, so not applicable to small lakes. Operational use dependent on Sentinel 3.	Minimal.
Medium resolution full-basin characterization	Land cover/use maps and change statistics.	Volta Basin, Lake Chad area	Overall accuracy of 80%. Kappa coefficient exceeding 0.7.	Designed for medium and coarse resolution data, so cannot resolve small-scale changes.	Minimal technical skills. Expert local knowledge needed for selection/labelling of classes.
Medium resolution land degradation index	Maps of areas with rainfall-independent, statistically-significant vegetation change.	Volta Basin, Lake Chad area	Vegetation trends were confirmed by local experts and other studies [18].	Applicable in rainfall limited ecosystems only.	Minimal.
Hydrological characterization	Historic and real-time precipitation, evapotranspiration.	Whole of Africa	Uses well-established datasets with documented accuracy [19,20].	Coarse spatial resolution.	Minimal.
High resolution basin characterization	Land cover/use maps.	Lake Chad area, South Africa, Namibia, Zambia.	Overall accuracy above 80%. Kappa coefficient exceeding 0.8.	Requires expert local knowledge or reference data.	Intermediate technical skills. Expert local knowledge needed for selection/labelling of classes.

Table 1. *Cont.*

Name	Key Output Variables	Region of Application	Accuracy/Performance	Limitations	Required User Skills
Water body mapping	Water extent mask.	Volta Basin, Lake Chad area, Zambia	Overall accuracy above 90%. Kappa coefficient exceeding 0.8.	Requires NIR and SWIR spectral information.	Intermediate technical skills.
Hydrological modelling	River discharge forecasts.	Kavango, Mokolo, Volta and Zambezi basins	Nash-Sutcliffe efficiency of 0.96 for 1-day forecast, 0.77 for 7-day forecast.	Requires field measurements of discharge for model calibration.	Advanced technical skills for model setup. Minimal technical skills for operational forecasting.
Flood mapping	Historical and real-time flood maps.	Nile basin in Sudan and Lake Chad basin	Overall accuracy of 0.95 to 0.99. Kappa coefficient between 0.64 and 0.75.	Lower accuracy in rough water surfaces, areas with partially submerged vegetation or desert regions.	Minimal

The demonstration cases had several stages. First, customized end-to-end processing workflows were developed for the requested use cases. The developed workflows were subsequently used for product derivation over significant areas and time periods, as requested by the users. Continental-scale products at 1–25 km resolution are already provided on an operational basis. In addition, trans-boundary products at 150–500 m covering in total over 17,000,000 km^2, basin-scale products at 2.5–30 m covering in total around 120,000 km^2 and local-scale products at 0.5–2.5 m covering in total some 300 km^2 were demonstrated with the WOIS to date on a number of African subsets chosen by the participating host institutions. The final step involved the testing of the workflows' stability/performance and ease of use, as well as evaluating the validity and usefulness of the outcome products in close dialogue with the users.

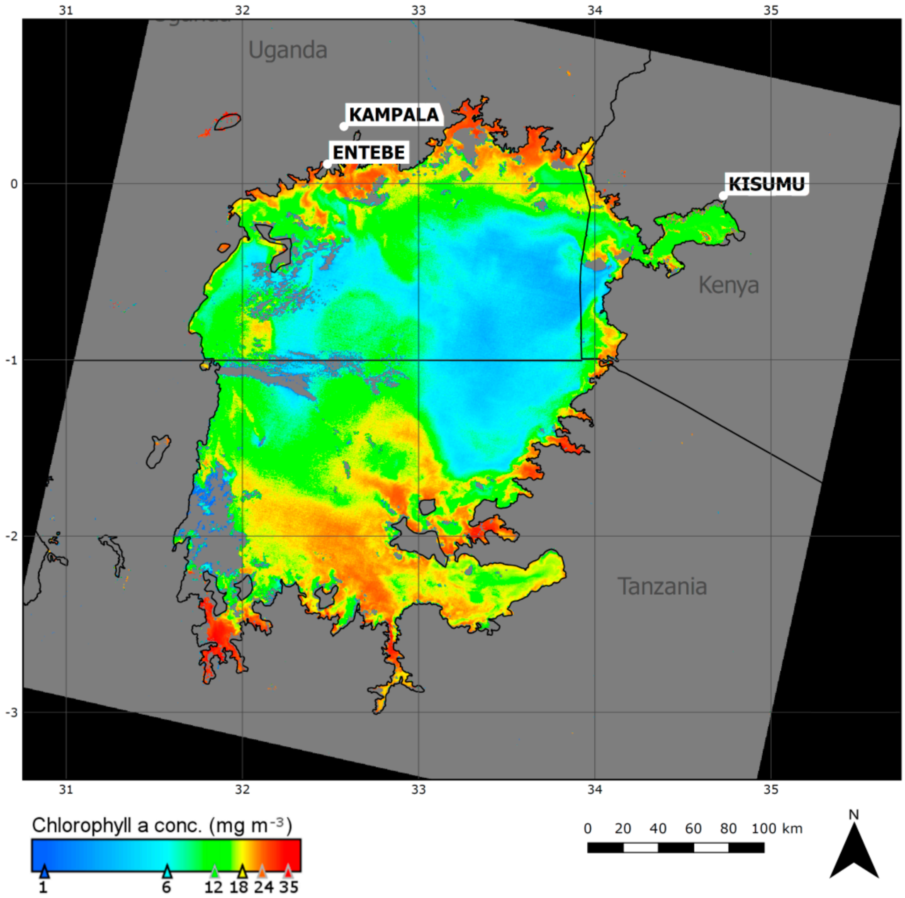
The following sections review five application cases in order to illustrate the use of WOIS for various tasks related to water resource management: monitoring of lake water quality, basin-wide land and hydrological characterization, high-resolution land and water characterization, hydrological modeling and flood monitoring.

3.1. Large Lakes Water Quality Monitoring

The provision of clean fresh water is a serious environmental challenge, and optical remote sensing has become an increasingly important tool for monitoring water quality on a regular basis. Therefore, WOIS provides workflows for estimating operational and historical, satellite-derived, water quality monitoring products for major lakes in Africa (Figure 3). The products can be used for, e.g., potential identification of point sources of pollution, the establishment of possible correlations with regular cholera outbreaks, better understanding of eutrophication processes and regular reporting obligations.

Under TIGER-NET, monitoring information about water quality and temperature is provided for Lake Chad and Lake Victoria using Envisat MERIS and AATSR (historic information) and MODIS AQUA (current information). Envisat data are processed using WOIS-embedded BEAM functionalities, including the eutrophic lakes processor, to derive water quality parameters (e.g., concentrations of chlorophyll and total suspended matter) from MERIS [21], and the Sea Surface Temperature (SST) processor, to obtain surface water temperature from AATSR data. Due to the failure of Envisat satellite in April 2012, the MODIS sensor on the AQUA satellite is being temporarily used for operational lake water quality and temperature observations. The MODIS data are processed by the TIGER-NET consortium using the L2 data processors available in SeaWiFS Data Analysis System (SeaDAS) [22] and then delivered to the WOIS database.

Figure 3. An example product from the WOIS workflow for monitoring lake water quality.



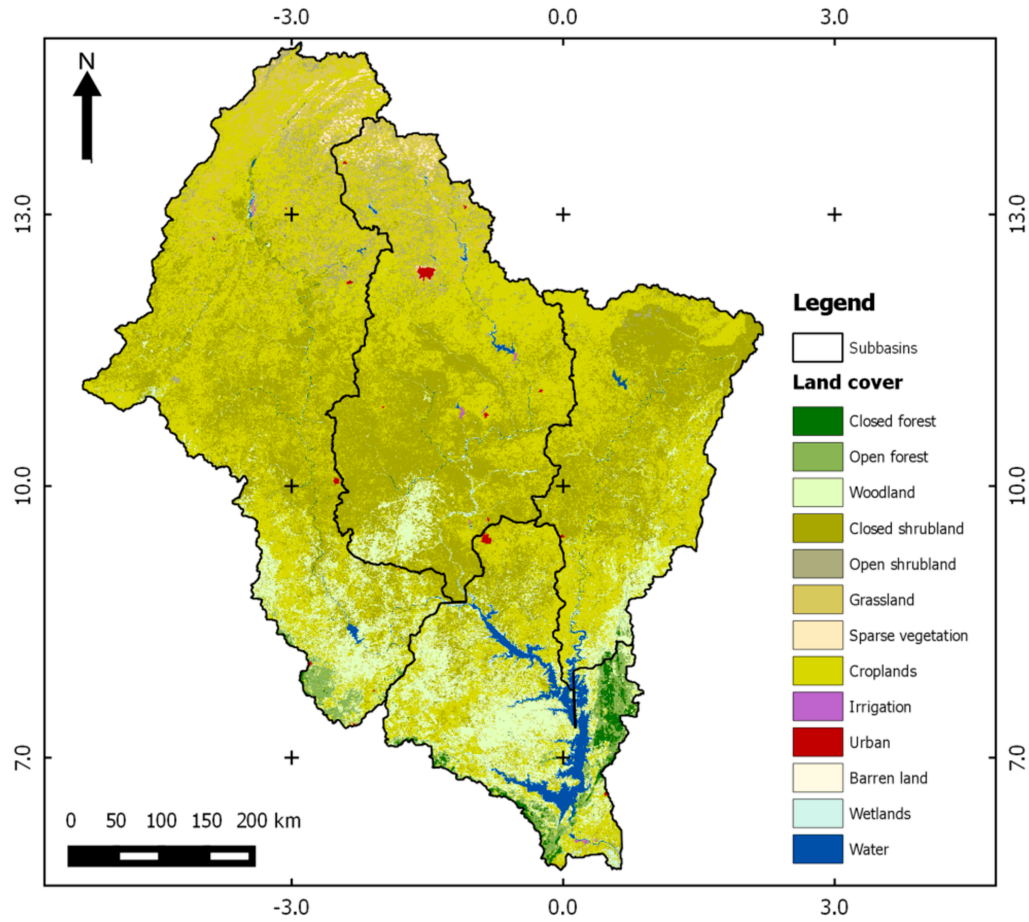
The validation of the water quality and temperature products has shown spatiotemporal variation in accordance with expected patterns. Especially the seasonal variation in lake surface temperature over both lakes is well captured in both historical and operational mode, hence underpinning the strong similarity of AATSR and MODIS AQUA temperature products. For the water quality products, the outcome is more ambiguous, as it depends on the performance of the processor for the specific lake. Looking past the extreme cases, the MERIS-derived concentrations of chlorophyll and total suspended matter exhibit spatial and temporal consistency with absolute values residing within the range of published numbers for both Lake Chad and Lake Victoria. The operational MODIS outputs show spatiotemporal patterns similar to the MERIS outputs over Lake Victoria, yet the output values are an order of magnitude lower, while the operational delivery of water quality products over Lake Chad is either impossible or inconsistent at best. The divergence between the two data sources is explained by the calibration range of the input algorithm for MODIS, which is designed for ocean color mapping and, thus, not ideal for inland lakes. The situation is expected to be rectified in the future, where data from the Sentinel 3 mission (expected to launch in 2015) will be used for the provision of water quality monitoring information through dedicated WOIS workflows.

3.2. Basin-Wide Characterization of Land and Water Resources

The basin-wide assessment and monitoring of hydrological system components and their interactions is very important for water resource management. Such components include large-scale land use changes, as well as regional precipitation, evapotranspiration and soil moisture estimates (including soil water index products), all of which are important for basin hydrology (e.g., by impacting runoff, streamflow or water availability) and for the current and future utilization potential of the land.

The WOIS includes six workflows, based mostly on the Orfeo Toolbox functionality, for basin-wide land use characterization and change detection analysis. For example, basin-wide land cover and land use maps can be derived from medium resolution imagery using either the supervised support vector machine [23] or the unsupervised *k*-means classifiers (Figure 4). Spectral changes between multi-temporal imagery can be analyzed using simple change detection algorithms, such as image differencing, as well as more advanced techniques, such as multivariate alteration detection and the maximum autocorrelation factor [24]. Thematic changes can be reported using a post-classification workflow, which returns the cross-tabulation of two input classification maps.

Figure 4. Recent land cover map of the Volta Basin derived using WOIS workflows for land cover mapping.

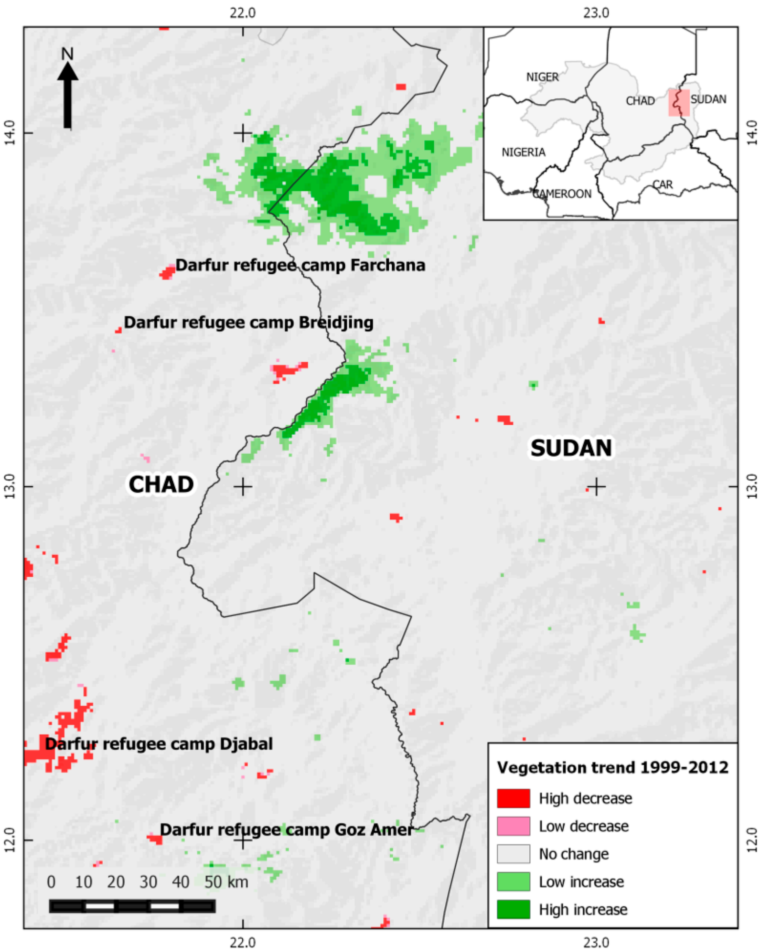


Basin-wide land degradation mapping can also be performed using a WOIS-embedded workflow. The WOIS implementation of the mapping method for land degradation uses mostly GRASS modules, with additional Python scripts to facilitate the processing of time-series data according to principles put forward in Huber *et al.* (2011) [25] and Hellden and Tottrup (2008) [26]. The workflow ingests gap-filled time series of NDVI (as a proxy for vegetation biomass [27]) and rainfall estimates in order to analyze vegetation/rainfall correlations and to control NDVI trends for variability in rainfall. NDVI residual time series, originating from regressing NDVI on rainfall, is subsequently searched for significant long-term trends in vegetation productivity, which is not related to rainfall, but possibly contributable to humans (e.g., population growth, changing land use practices, deforestation, infrastructure developments, as well as rural exodus and urbanization). Full basin assessments of land cover and land use changes, as well as land degradation processes have been successfully demonstrated for Lake Chad and Volta Basin using medium resolution imagery from MODIS and SPOT VGT. When evaluated against higher resolution imagery (e.g., Landsat and Google Earth), the overall accuracy of the land cover/land use products was assessed to be around 80%, with a kappa coefficient of agreement exceeding 0.7. High resolution imagery also supported the validation of the land degradation analysis, yet the causes behind the observed vegetation trends are often manifold, and hence, local experts were consulted to verify and give reasons for distinctive negative or positive vegetation trends. The local experts were able to explain most of the negative vegetation trends with urbanization, dam constructions and deforestation, while positive vegetation trends were mostly associated with protected areas and irrigated lands. A particular interesting trend pattern was observed along the border area of Chad and Sudan. Here, large areas with strong positive vegetation trends appear on the Sudanese side, while pockets of negative vegetation trends are spotted on the Chad side. The reasoning behind this pattern is explained by population displacement as a consequence of the conflict in Darfur (Figure 5) and as corroborated by other studies [18].

The WOIS workflows for basin-wide land characterizations have proved useful for the provision of ground cover information needed for water resource management and planning, as well as establishing the baseline information from which monitoring activities can be performed. Still, the workflows are designed for being used with medium to coarse resolution data, and hence, both land cover transitions and land cover changes may be obscured by the resolving power of the data. Results should therefore not be interpreted as undeniable facts and the area measurements provided certainly not perceived as accurate, but they do indicate a trend that is likely to be real and most likely in the right order of magnitude.

Contrary to the land characterization products, which are the result of dedicated image processing workflows, the integration of the hydrological characterization products into the WOIS database is mainly based on facilitating linkages to external data providers. For example, the near-real-time rainfall data product is downloaded directly from the NOAA Climate Prediction Center [19] (http://nomads.ncep.noaa.gov/ (accessed on 10 June 2014)) through a WOIS workflow, which also allows the user to calculate accumulated rainfall or subset the downloaded images, while the Land Surface Analysis Satellite Applications Facility (LSA-SAF) evapotranspiration product [20] (http://landsaf.meteo.pt/algorithms.jsp?seltab=7&starttab=7 (accessed on 10 June 2014)) is first preprocessed (subsetted and reprojected) by the TIGER-NET consortium before being made available on the TIGER-NET FTP server. All hydrological characterization products have Pan-African coverage and, hence, are available to all users who can download the products using a WOIS-embedded workflow.

Figure 5. Land degradation in Eastern Chad caused by the war in Sudan's Darfur region. Since 2003, over 3000 villages have been destroyed and hundreds of thousands of people have been displaced into refugee camps in neighboring Chad. These areas are clearly visible in satellite data, as growing camp sites and use of natural resources have caused a vegetation decline. On the other hand, the Sudan side shows signs of vegetation greening caused by agricultural land abandonment as forced by the population displacement.

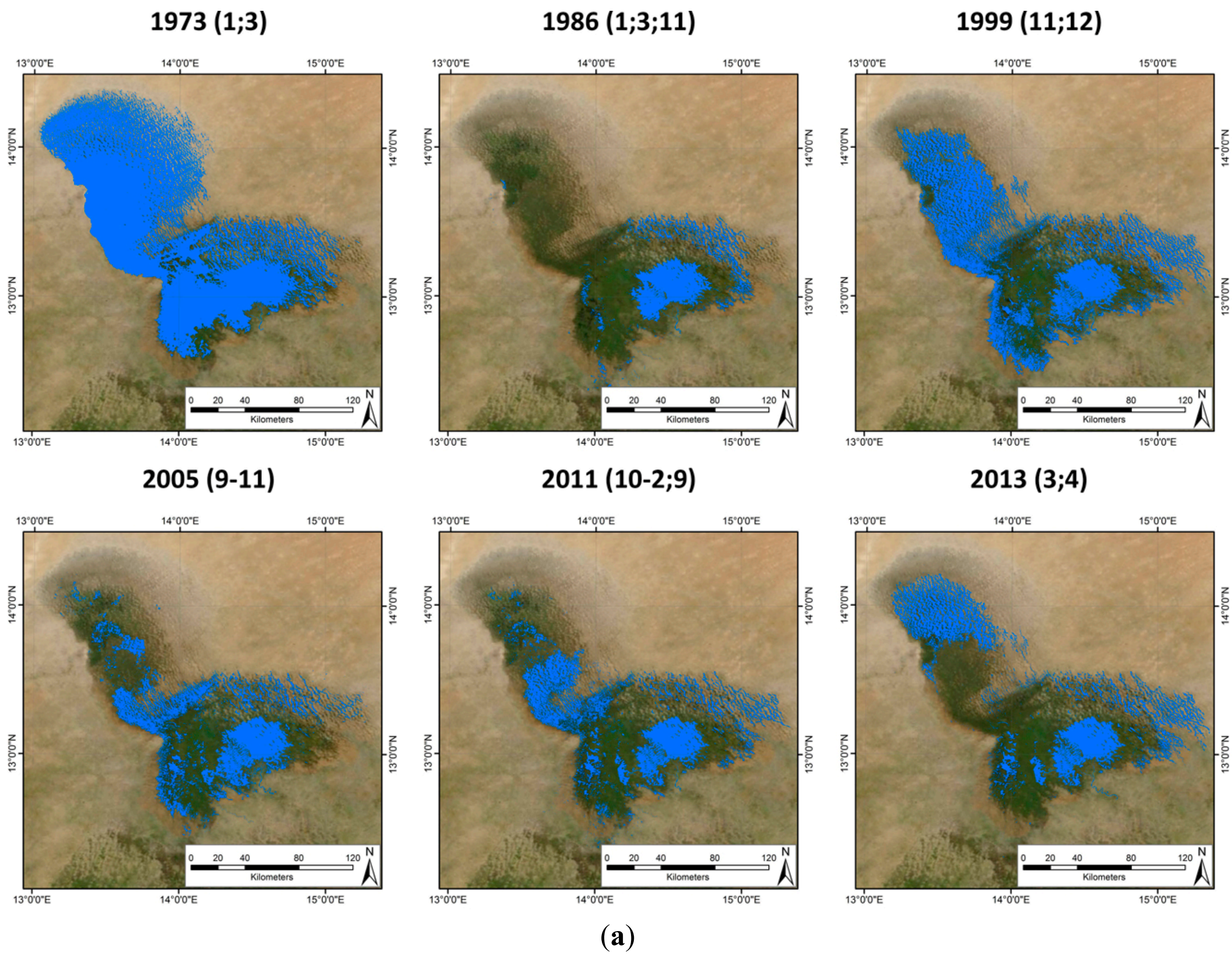


3.3. High Resolution Land and Water Characterization

Mapping land cover at the sub-basin level with high resolution (5–20 m pixel size) EO observations has many practical applications in water management and water resource accounting. Those applications include tracking seasonal and long-term land cover changes (disappearance of vegetation, change of mining or cropland areas), observing the capacity and location of small water bodies and delineating lake shorelines and wetlands. From the regional water demand perspective, accurate mapping of "cultivated areas" (irrigated and non-irrigated) and "urban areas" (residential and commercial/industrial) was deemed of high importance by the participating water authorities.

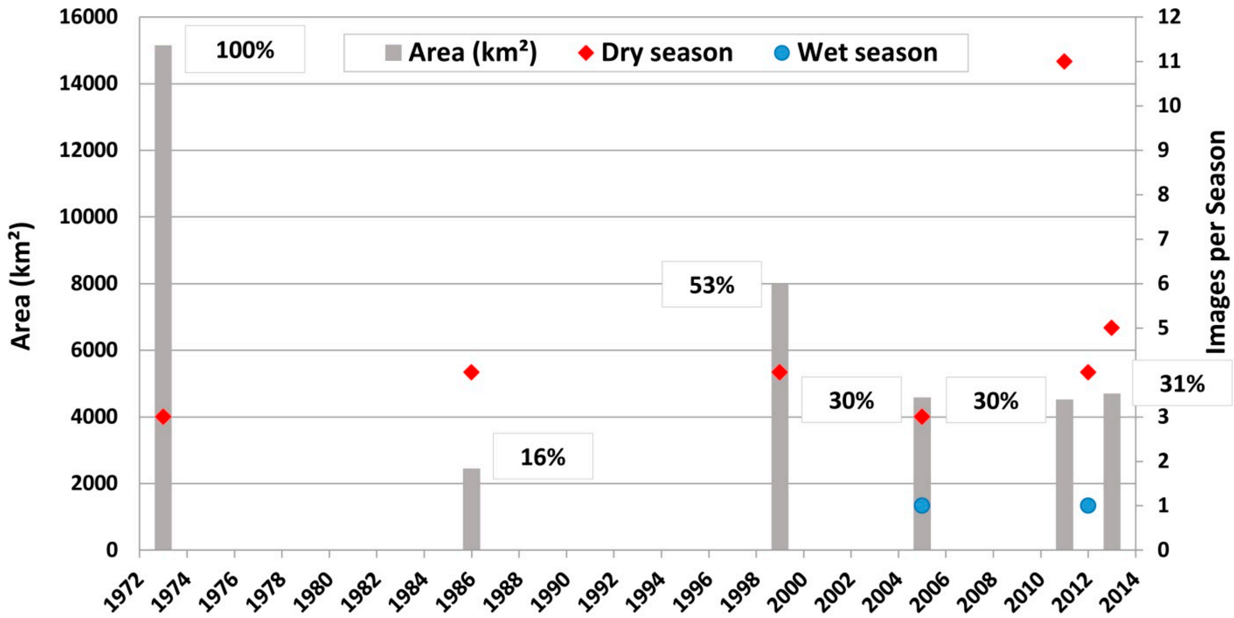
The methodology implemented in the relevant WOIS workflows follows an automated, hybrid pixel- and object-based EO image classification approach, based on the multi-spectral and spatial properties of the satellite imagery, followed by stringent post-processing rules for refinement of the results. As the main pixel-based approach, an unsupervised *k*-means classification method was selected [28]. The segment-based classification process consists of two steps: image segmentation and classification, both controlled by a dedicated rule set aimed at being as simple as possible to ease method transfer to other regions, but as complex as necessary for the desired results [29]. The outputs of the two approaches were fused, based on spatial statistics per land cover type, thus combining the advantages of both classification methods. The workflows allow the possibility of including point sampling data in the processing chain, thus ensuring the participation of local experts during the production and validation phases.

Figure 6. (**a**) Lake Chad historic water extent (indicated in blue) as determined using WOIS. The numbers in brackets on top of each image indicate the months of acquisition of high resolution images used for deriving the water extent for a given year. For the extent in year 2011, images from 2011 and 2012 were used. (**b**) Area statistics of Lake Chad historic water extent shown in (a). The grey bar indicates water area in km^2 (left axis) with the percentage above each bar showing the size of the area relative to year 1973. Red diamonds and blue dots indicate the number of images in dry and wet seasons, respectively, used to estimate the water extent in a given year (right axis). Note that images from 2012 were used for estimating water extent in 2011.



(**a**)

Figure 6. *Cont.*



(**b**)

The WOIS high resolution land and water mapping tools were so far successfully implemented for seasonal small water body mapping in the Volta Basin and for mapping water demand-related land cover changes in sub-basins of South Africa. They are currently being implemented for, among others, flood vulnerability mapping in Namibia, as well as for dam monitoring in sub-basins of Zambia. The system components have further been employed by the Lake Chad Basin Commission for assessing in detail the historic changes of the Lake Chad area extent (Figure 6) and its surrounding basin land cover changes, documented in the first Lake Chad Biannual Environmental Report. The historic water area extent has been estimated for a number of selected years (Figure 6a) from the maximum water extent derived from a composite of high resolution images for each year, taken predominantly during the dry season (Figure 6b). It has been shown that despite the significant decrease of Lake Chad in the 1980s, the area of water bodies has nearly doubled from 1986 to 2011, resulting in a significant change in vegetation cover and land use in the basin originally occupied by the lake. The results are directly employed to control and evaluate water management regulations in the basin.

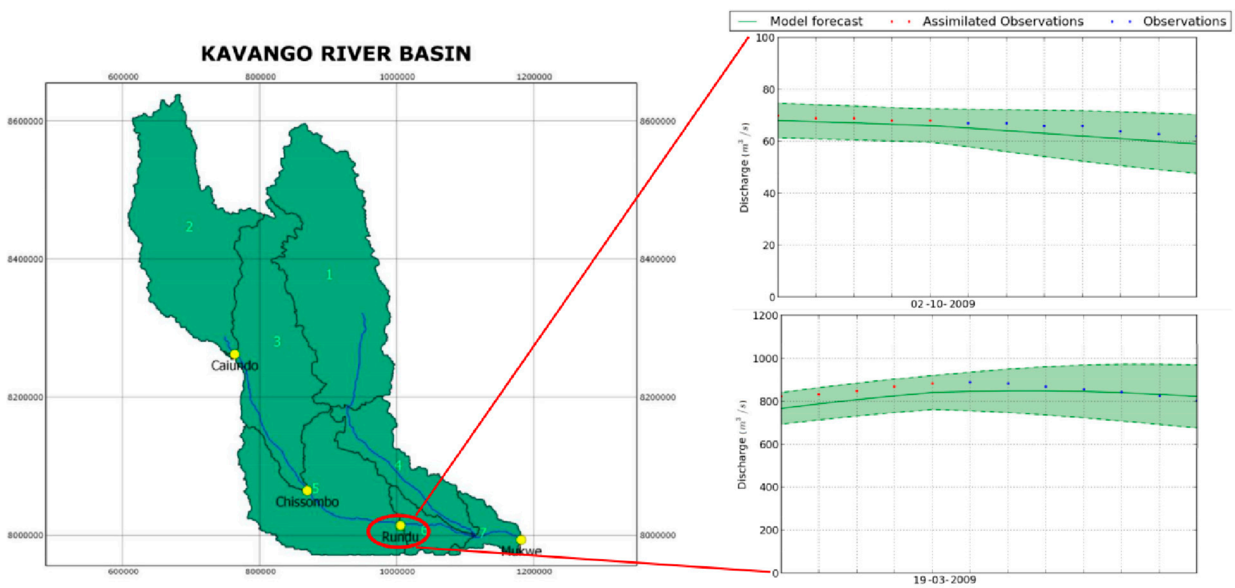
High resolution land cover characterization remains challenging, and the provided tools do not compensate for good user skills regarding image interpretation and classification. The tools provide instruments to derive and characterize, leaving it up to the user to choose the best fitting method and combination in order to achieve adequate results.

3.4. Hydrological Modeling Framework for Real-Time Water Discharge and Flood Forecasting

Hydrological models (HMs) are key decision support tools for integrated water resources management. HMs are quantitative computer simulation engines used to reproduce and analyze the interactions of all relevant hydrological processes and water users in a river basin. They provide answers to "what-if" questions, both in the context of long-term planning and real-time operational management decisions. Long-term planning problems arise because land-use practices, water demands and water-related risks are constantly changing over time. Moreover, as a consequence of global climate and land use changes, the probability distributions for many hydrological variables are starting to change (e.g., [30]). Real-time management problems arise because of the occurrence of extreme hydrological events. The optimal response to such extreme events depends on the actual state of the hydrological system, and real-time information on the system state is thus essential.

In the context of real-time operational water resources management, data assimilation (DA) has become the state-of-the-art technique to merge model predictions with the latest available data from a variety of sensors, including *in situ* and satellite-borne instruments. Assimilation of *in situ* data has become standard practice in most operational flood forecasting models (e.g., [31]). Many operational hydrological forecasting systems use variants of the Kalman filter [32] for data assimilation. In particular, the extended Kalman filter (EKF, [33]) and the ensemble Kalman filter (EnKF, [34]) are widely used in hydrological applications, since they are suitable for non-linear problems.

Figure 7. Example river discharge seven-day forecast for low flow conditions (**top right**) and high flow condition (**bottom right**) for the station Rundu on the Kavango River in Namibia, issued for October and March 2009 respectively. The solid green line is the central model forecast, and the green shaded area is the confidence interval of the forecast. Red dots are assimilated observations, and blue dots are daily observations after the issue date of the forecast.



The HM implemented in the WOIS is the SWAT model, which is an open-source, physically-based, semi-distributed hydrological model developed and maintained by the U.S. Department of Agriculture [35]. SWAT hydrological response is not computed on grid cells, but instead on variably sized hydrological response units (HRU), which are portions of the sub-basins having unique combinations of slope, land cover and soil type. WOIS SWAT models are parameterized with global elevation, land-cover and soil type datasets and are forced with climate data from European Centre for Medium-Range Weather Forecasts (ECMWF) [36], Famine Early Warning Systems Network-Rainfall Estimate (FEWS-RFE) [37] or National Oceanic and Atmospheric Administration-Global Forecast

System (NOAA-GFS) [38]. Automatic SWAT model calibration is performed with the public-domain software, PEST [39,40]. PEST provides a local gradient search algorithm, as well as a shuffled complex evolution algorithm for global search.

The WOIS operational forecasting approach (Figure 7) uses the EKF to assimilate water discharge measurements from any available monitoring stations into the SWAT hydrological model and is driven by NOAA-GFS eight-day ahead atmospheric forecasts. The approach is presented in detail in [41]. The set-up and calibration of WOIS SWAT models for a number of case study basins are documented in [42–44]. The WOIS operational forecasting approach has been implemented for the Kavango and Mokolo basins and is presently being implemented for the Volta and Zambezi basins. Daily Kavango forecasts are used operationally by the Namibian Ministry of Agriculture, Water and Forestry. In Kavango, forecast skill ranges from a Nash-Sutcliffe efficiency (NSE) of 0.96 for the one-day horizon to 0.77 for the seven-day horizon. The quality of the precipitation forcing product has the most significant impact on forecast skill. Key assumptions in the forecasting system are related to the representation of modeling and observation errors.

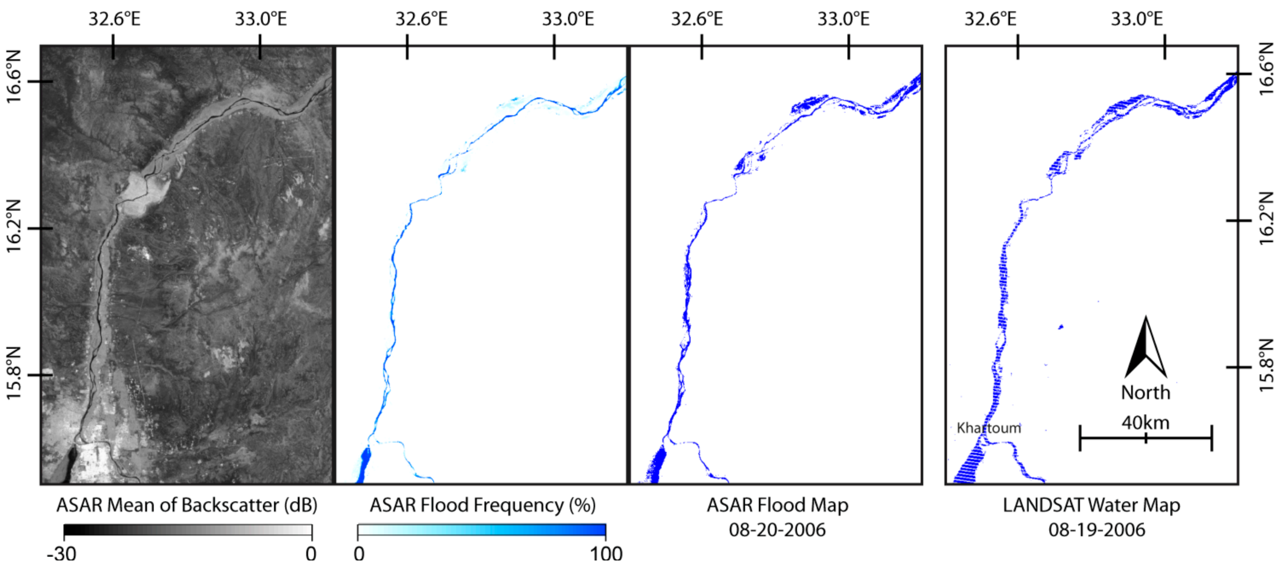
3.5. Historic and Real-Time Flood Mapping and Monitoring

With a constantly increasing density of population, flood-related economic and social risks increase. The monitoring of floods using data from synthetic aperture radar (SAR) has been exploited during the last thirty years and has proven to be well suited for understanding the spatio-temporal flood characteristics. The major advantage of using SAR compared to optical and infrared imagery lies in its ability to penetrate clouds and vegetation cover. In addition, it presents a significant improvement in spatial resolution when compared to coarse resolution microwave products (*i.e.*, ASCAT, AMSR-E, SMOS).

The flood mapping methodology used in the WOIS uses primarily ASAR Wide Swath (WS) mode data at 150-m resolution for historic flood mapping and RADARSAT imagery for near-real-time flood mapping. The methodology workflow consists of pre-processing, classification and post-processing steps. In the pre-processing step, precise orbit vectors and range-Doppler terrain correction are applied to obtain a georeferenced SAR image. The classification module of the WOIS workflow relies on the specular reflection properties of calm water surfaces, which appear dark in the resulting SAR imagery. Within the WOIS, both an automatic and a manual thresholding approach are implemented. In the case of manual thresholding, the user can plot the histogram of the SAR image reflectance, which helps to determine a suitable threshold value. The automatic thresholding comprises a combination of image tiling inspired by Martinis *et al.* [45] and Otsu's histogram thresholding method [46]. Finally, to mask out areas that are not prone to flooding and to remove pixels falsely classified as water due to topography-induced radar shadows, the Height Above Nearest Drainage (HAND) [47] index is used, which consists of the relative height of a cell in the digital elevation model (DEM) w.r.t. the closest DEM cell pertaining to the drainage network. The distance to the drainage network is measured along the flow lines of water in the DEM. The HAND index was based on the HYDROSHEDS database [48].

The demonstration cases for the historical flood mapping in the TIGER-NET project were the southern Nile Basin (NB) in Sudan and the Lake Chad Basin (LCB). The total accuracy of the derived product when compared with water maps derived from the NDVI-NDWI indices retrieved from LANDSAT-7 imagery were 0.95 and 0.99 over Sudan and Chad, respectively. The kappa coefficients for the validated scenes were on average 0.75 in the NB and 0.64 in the LCB demonstration case. As an example, Figure 8 shows a significant flood event near Khartoum city along the Nile River and surroundings captured by ASAR on 20 August 2006. Figure 8, right, illustrates the flood scene extracted from the Landsat-7 acquisition from the day before. According to the reports, the flood started at the beginning of August, due to heavy rain, and increased to a large-scale emergency by August 25. Twenty seven people were killed, and about 10,000 houses were damaged [49,50].

Figure 8. Northeast of Khartoum city, Sudan. Comparison of the ASAR flood map from 20 August 2006, with the Landsat-7 ETM+ water map produced by thresholding of the NDWI-NDVI index from 19 August 2006.



It was found that the accuracy of the final products deteriorates with roughening of the water surface or with partially submerged vegetation. Furthermore, in the desert regions, the low differences in backscatter levels between bare ground and water surfaces may exert risks on the quality of the final flood product.

4. Outlook and Conclusions

Current water management practices in Africa are hampered by sparse and unreliable information on water resource availability. The Water Observation and Information System (WOIS) was created to support African institutions in improving their Integrated Water Resource Management (IWRM) by exploiting the advantages of Earth observation (EO) technology. The WOIS has been designed and developed as a user-friendly, yet powerful multipurpose system supporting the full range of EO products and models needed for assessing, monitoring and inventorying water resources from sub-catchment to river basin levels. It contains over 40 workflows to guide the less experienced users through EO data processing and GIS analysis in order to derive products required for IWRM. The validity and accuracy of those products has been assessed through numerous demonstration cases.

For example, medium resolution land cover maps derived with WOIS have been shown to have a kappa coefficient above 0.7; high resolution water body mapping achieved kappa exceeding 0.8; and SAR-derived flood maps reached an overall accuracy of 0.95 to 0.99, while hydrological modeling resulted in forecast skill with a Nash–Sutcliffe efficiency of 0.77 for a seven-day forecast.

The development of the WOIS represents a successful example of a user-driven and collaborative development model, where functionalities have been designed, developed and evaluated through user-designated cases in order to demonstrate the real impact of the system on enhancing water management and integrated water resource management plans. The WOIS is already implemented in major African river basin authorities, several African ministries and agencies, as well as in research and humanitarian organizations, and new users are expected once the source code is released. It will therefore continue to develop in response to continued user requirements for new functionalities and functional improvements and due to general software, algorithm and method enhancements. A particular focus will be to ensure the support and implementation of processing capacity for the upcoming Sentinel satellite systems by integrating the ESA Sentinel toolboxes and developing dedicated production workflows, which will turn WOIS into a fully-operational monitoring system.

Through provision of this free, powerful and extendable system in combination with continued capacity building and training efforts, the TIGER-NET project strives to build the basis for an extension, *i.e.*, to roll-out to other countries and regions in Africa and beyond. Another major aim is the continued support of the users and stakeholders in order to reach sustainability by attracting external funding opportunities to enable operational utilization of satellite data for Integrated Water Resource Management in Africa. More information about the WOIS software and the TIGER-NET project can be found on the project's website: tiger-net.org.

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Author Contributions

Radoslaw Guzinski has been responsible for the WOIS system design, development and implementation. Steve Kass has been responsible for the high resolution land and water characterization component. Silvia Huber has been responsible for large lake water quality monitoring and land degradation mapping. Peter Bauer-Gottwein and Iris Hedegaard Jensen have been responsible for the implementation of the WOIS hydrological modeling and forecasting component. Vahid Naeimi and Marcela Doubkova have been responsible for the implementation of historic and real-time flood mapping and monitoring component. Andreas Walli has been the TIGER-NET project manager and responsible for eliciting and documenting user requirements. Christian Tottrup has been responsible for the overall design and system engineering, as well as the implementation of the basin-wide characterization of land and water resources.

Conflicts of Interest

The authors declare no conflict of interest.

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